Journal of Advanced Research (2015) 6, 833–838

Cairo University

Journal of Advanced Research

ORIGINAL ARTICLE

Structural mass irregularities and fiber volume influence on morphology and mechanical properties of unsaturated polyester resin in matrix composites

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Khalil Ahmed [a,*], Muhammad Nasir [b,*], Nasreen Fatima [b], Khalid M. Khan [c], Durey N. Zahra [c]

[a] *Applied Chemistry Research Centre, Pakistan Council of Scientific & Industrial Research Laboratories Complex, Karachi 75280, Pakistan*
[b] *Department of Chemistry, University of Karachi, Karachi 75270, Pakistan*
[c] *H.E.J. Research Institute of Chemistry, International Center for Chemical and Biological Sciences, University of Karachi, Karachi 75270, Pakistan*

A R T I C L E   I N F O

Article history:
Received 1 April 2014
Received in revised form 21 June 2014
Accepted 25 June 2014
Available online 1 July 2014

Keywords:
Structural mass irregularities
Cotton fiber
Polymeric composite
Morphology
Mechanical properties

A B S T R A C T

This paper presents the comparative results of a current study on unsaturated polyester resin (UPR) matrix composites processed by filament winding method, with cotton spun yarn of different mass irregularities and two different volume fractions. Physical and mechanical properties were measured, namely ultimate stress, stiffness, elongation%. The mechanical properties of the composites increased significantly with the increase in the fiber volume fraction in agreement with the Counto model. Mass irregularities in the yarn structure were quantitatively measured and visualized by scanning electron microscopy (SEM). Mass irregularities cause marked decrease in relative strength about 25% and 33% which increases with fiber volume fraction. Ultimate stress and stiffness increases with fiber volume fraction and is always higher for yarn with less mass irregularities.

Introduction

Plant fiber as reinforcing agent in the preparation of composite material, is getting more attention of the researcher due to its eco-environmental advantages over petroleum based fibers [1]. Natural fibers such as coir [2], bamboo [3], flax [4], kenaf [5], sisal [6] and jute [7] have extensively been used as reinforcing agents with comparable mechanical properties. These fibers were used in different forms such as continuous, random,

* Corresponding authors. Tel.: +92 21 34690350; fax: +92 21 3464184.
E-mail addresses: khalilmsrc@gmail.com (K. Ahmed), chemistnasir@yahoo.com (M. Nasir).
Peer review under responsibility of Cairo University.

ELSEVIER Production and hosting by Elsevier

2090-1232
http://dx.doi.org/10.1016/j.jare.2014.06.007

and oriented fibers. Literature shows that the main focus of the researchers' world over is to improve and relate the mechanical properties of the composite to surface modification [8], orientation [9] and content of fibers [10]. Textile yarn/fabric of different natural fibers has also been used as reinforcing agent in composites [11,12]. More recently a study was carried out to propose a model to describe the effect of yarn twist on the tensile strength of unidirectional plant fiber yarn composites [13].

Various studies are available on properties of aligned plant fiber composites focusing mechanical properties with fiber direction and volume fraction [14–21]. Presented in this paper are preliminary results of a larger study set out to investigate the mass irregularities and unevenness of spun yarn/chemically treated spun yarn and their effect on compatibility, physical properties and mechanical behavior of yarn composites. This research shows the combined effect fiber volume and mass irregularities, the variation in mass per unit length of yarn, on the mechanical properties of UPR matrix composites reinforced with spun yarn processed by filament winding method.

The main and unavoidable type of mass irregularities in yarns is due to random, short and immature natural fibers [22]. This type of mass irregularities in the yarn can be minimized by removing short and immature fibers during combing process in textile industry.

The mass irregularities in yarn structure were measured by uster evenness testing system, and its effect on physical structure of fibers in fiber bundle of yarn was analyzed by scanning electron microscopy. The results showed that mass irregularities in the structure of yarn affect the alignment of fibers at microlevel in the fiber bundle as a result average diameter varies. The average diameter of the yarn and composite was measured through SEM images to investigate and compare the mechanical properties such as ultimate stress and stiffness.

Experimental

Materials

This work is concerned with the comparative study of unsaturated polyester resin matrix composite materials reinforced with aligned yarn having different mass irregularities. The unsaturated polyester resin (UPR) used in this study was a commercial product of Al-Khair Industries, Karachi-Pakistan. Resin comprises 40% by weight styrene, with an average of 5.88 vinylene groups per unsaturated polyester molecules. The average molecular weight of the unsaturated polyester resin is 2750 g/mol and the equivalent molecular weight/(mol C=C) is 468 g/mol. The molar ratio of styrene/unsaturated polyester resin is 2.7. The unsaturated polyester resin was employed as received without removing the inhibitor.

Samples of yarn with same count (i.e., 20NE/1, 100% cotton) and different mass irregularities were taken from Fazal Textile Mills, Karachi, Pakistan.

Methods

Conditioning

Prior any testing spun yarns were conditioned under standard conditions of 20 °C ± 2 °C and 65 ± 3% relative humidity (RH) for 24 h.

Yarn mass irregularity

Yarn mass irregularity was quantitatively measured as unevenness%, CV%, thin, thick, neps and hairiness present in yarn. Uster Technologies 4-SX evenness tester (Switzerland) was used to measure its evenness according to ASTM D1425.

Composite formation

The yarn was aligned by filament-winding machine on to a metal frame producing yarn assemblies with a high degree of alignment and controlled thickness shown in Fig. 1. Composite laminates were prepared with onefold of yarn with varying amount of resin to get the desired volume fraction of yarn. The mechanical properties of composites were determined in axial direction of yarn. The metal plate was fitted in the middle of a special type of die cast. Specific amount of resin, initiator and our recently developed promoter system [23] were transferred using RTM method. The laminate composites were then left for 2 h at room temperature for complete dryness.

The fabricated composite laminates were $300 \times 500\ mm^2$ with a variable thickness of 2.0–2.9 mm. Samples of composites were produced with volume fractions (V_f) of 0.305 and 0.408 of yarn with varying quantity of mass irregularities.

SEM analysis

Mass irregularity and micro-alignment of fibers in yarn and its composite were analyzed by scanning electron microscope (SEM) model # 6380A JEOL (Japan). The samples were first coated with autocoater Model No. JFC-1500 JEOL (Japan).

Tensile properties of yarn

Tensile properties of spun yarn were measured according to ASTM D2256. Standard Test Method for Tensile Properties of Yarns by the single-strand method was used to measure single yarn breaking strength by Uster Technologies Tensorapid III. The testing speed was adjusted 500 mm/min, and the gauge length was 500 mm. The sample size was 5 and each sample was tested ten times. The yarns were picked automatically with programmed software and results were collected as print file.

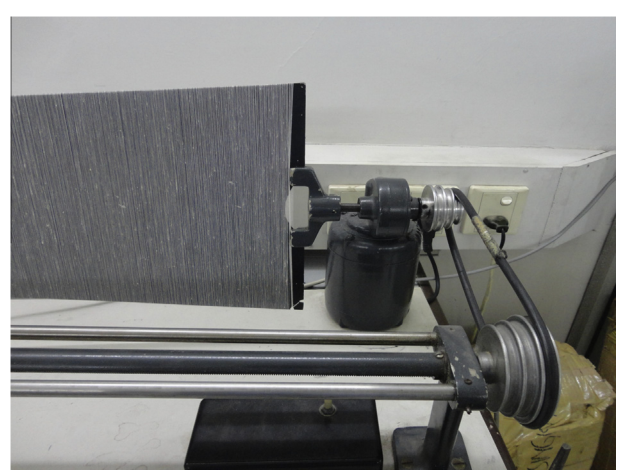

Fig. 1 Filament winding machine.

Tensile properties of composites

The axial tensile properties were investigated using universal testing machine (Instron 4301) according to ASTM D 638. The capacity of machine was 5 kN. The tensile strength was measured at a crosshead speed of 1.0 mm/min. Gauge length was 50 mm. The sample was 5 numbers and tests were performed after 24 h of composite mold at room temperature.

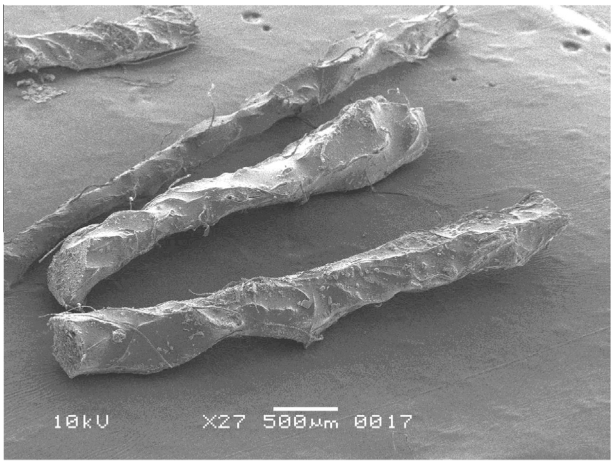

Fig. 2 SEM of composites.

Table 1 Characteristics, units and description of Mass irregularity Parameters of yarn.

Characteristics	Unit	Description
U	%	Linear irregularity
CV m	%	Coefficient of variation of the yarn mass
CV m (L)	%	Coefficient of variation of the yarn mass at cut length 1, 3, 10 and inert
Imperfections		Number of thin places, thick places and neps selected sensitivity setting. Thin places: −50%, Thick places: +50%, Neps: +200%
H		The hairiness H corresponds to the total length of protruding fibers divided by the length of the sensor of 1 cm. The hairiness is, therefore, a figure without a unit

Results and discussion

Mass irregularities in plant fibers/yarns are one of the factors that also influences the mechanical properties of these fiber reinforced polymeric composites. Their impact on mechanical properties of materials is due to the formation of kinks and thin with spillage of fibers which reduced the microalignment of fibers within the yarn. The presence of kinks, thin and thick in the fiber structure discontinues the penetration of resin in the fiber bundles of yarn and form irregular surface which can be seen in Fig. 2. Therefore, nonuniform diffusion of thick resin influences the stress bearing properties of fibers and their composite materials and show relatively less strength. Two samples namely sample-1 and sample-2 were used in the characterization of mass irregularities and their impact on mechanical properties of yarn and composites. Yarn with less mass irregularities was denoted as sample-1 and sample-2 with more mass irregularities.

Characterization of yarn mass irregularity

Quantitative mass irregularities in yarn structure were measured using the parameters such as unevenness%, thick, thin, CV%, hairiness. These parameters are normally used in textile for the detection of faults in yarns but in our case we are measuring their effect on mechanical properties of the composites. Table 1 shows the characteristics, units and description of the parameters of mass irregularity in the yarn structure.

Tables 2a and 2b show the result from measuring the mass irregularity parameters. It is clear from the tables that sample-1 has zero thin, a very few thick and neps with in the yarn. Similarly, if we see other parameters such as hairiness, different modes of CV of both yarns, it can be stated that fibers of sample-1 have more microalignment than sample-2.

Spectrogram

Spectrogram expressed the periodical mass irregularity in the yarn. Higher mass irregularity (CV) in yarn appears as higher peaks in spectrogram. It is evident from Fig. 3a that sample-1 yarn has short-term irregularity on wavelengths λ = (28–30)

Table 2a Mass irregularity parameters of Sample-1.

S. no.	U %	CV m	CV 1 m	CV 3 m	CV 10 m	CV inert	Thin −50%	Thick +50%	Neps +200%	H
1	8.23	10.38	3.26	2.6	1.67	1.3	0	7.5	5	5.77
2	8.43	10.59	3.42	2.74	1.85	1.5	0	0	5	6.03
3	8.49	10.7	3.79	3.06	2.36	1.88	0	5	7.5	5.82
4	8.23	10.48	3.38	2.56	1.85	1.53	0	15	15	6.02
5	8.35	10.53	3.33	2.36	1.72	1.4	0	2.5	7.5	5.85
6	8.47	10.65	3.38	2.37	1.72	1.37	0	0	5	5.99
7	8.49	10.72	3.32	2.56	1.3	0.88	0	5	5	5.64
8	8.52	10.76	3.78	3.05	2.21	1.85	0	5	2.5	6.15
9	8.2	10.31	3	2.48	1.8	1.62	0	5	5	6.27
10	8.57	10.82	3.61	2.87	2.02	1.66	0	7.5	12.5	5.77
Mean	8.4	10.6	3.43	2.66	1.85	1.5	0	5.3	7	5.93
Max	8.57	10.82	3.79	3.06	2.36	1.88	0	15	15	6.27
Min	8.2	10.31	3	2.36	1.3	0.88	0	0	2.5	5.64

Table 2b Mass irregularity parameters of Sample-2.

S. no.	U %	CV m	CV 1 m	CV 3 m	CV 10 m	CV inert	Thin − 50%	Thick + 50%	Neps + 200%	H
1	10.86	13.86	4.79	3.69	2.62	2.02	0	122.5	102.5	6.41
2	10.47	13.29	3.99	3.02	1.94	1.46	0	77.5	82.5	6.68
3	10.63	13.51	4.17	3.14	1.96	1.25	0	95	115	6.88
4	10.45	13.27	3.99	3.02	1.89	1.63	0	87.5	90	6.45
5	10.66	13.53	4.64	3.65	2.71	2.39	0	70	125	6.43
6	10.34	13.12	3.92	3.05	1.83	1.21	0	72.5	75	6.37
7	10.62	13.38	4.25	2.94	1.93	1.52	0	62.5	110	6.41
8	10.28	13.07	3.98	3.18	2.3	1.47	0	65	92.5	6.72
9	10.16	12.94	3.8	2.82	1.96	1.44	2.5	82.5	110	6.49
10	10.99	13.92	5.1	3.99	2.97	2.46	0	100	132.5	6.3
Mean	10.55	13.39	4.27	3.25	2.21	1.69	0.3	83.5	103.5	6.52
Max	10.99	13.92	5.1	3.99	2.97	2.46	2.5	122.5	132.5	6.88
Min	10.16	12.94	3.8	2.82	1.83	1.21	0	62.5	75	6.3

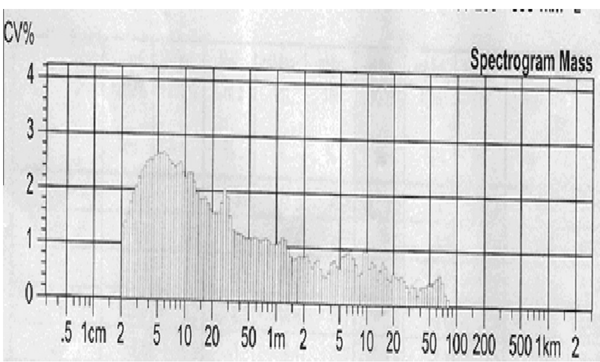

Fig. 3a Spectrogram of sample-1.

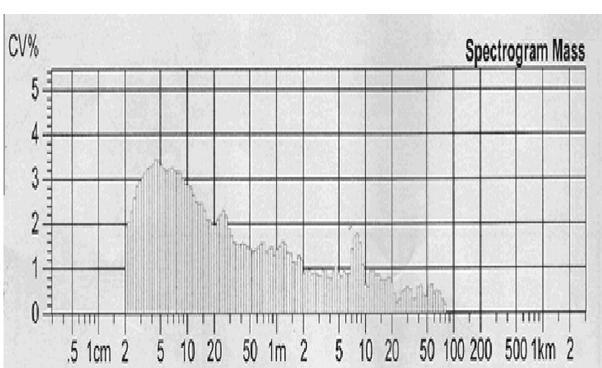

Fig. 3b Spectrogram of sample-2.

cm with 2.0% CV, the shape of spectrogram embodies no other faults, whereas the spectrogram of sample-2 yarn Fig. 3b has short-term irregularity on wavelengths λ = (22–30) cm with 2.4% CV, along with an increased in amplitude on wavelength λ = 8–9 m with 1.8% CV.

Scanning electron microscopy (SEM) studies of mass irregularity and microalignment of fibers in the fiber bundles of yarn

Mass irregularities in structure that also affect the microalignment of fibers can be seen in SEM images of sample-1 and

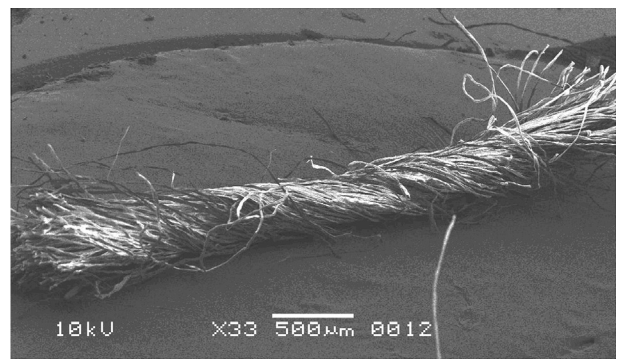

Fig. 4a SEM of sample-1.

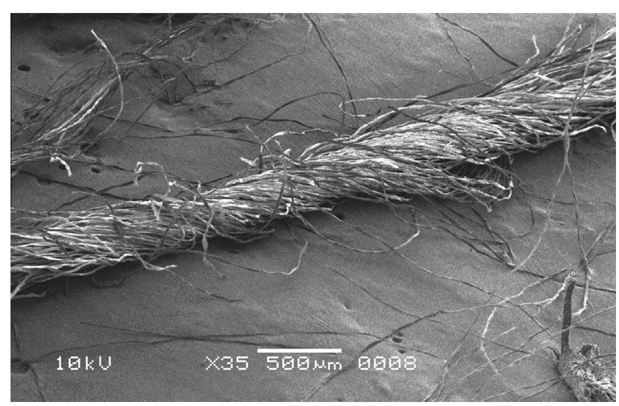

Fig. 4b SEM of sample-2.

sample-2 of yarn. Figs. 4a and 4b show the non-aligned fibers become thick, thin, neps and hairiness in yarn.

Characterization of yarn tensile properties

After characterization of mass irregularity in yarn structural, we measured tensile properties of both sample-1 and sample-2. Table 3 shows the characteristics, units and description of the parameters that we measured in order to compare the yarn tensile properties in relevance to structural mass irregularities.

Table 3 Characteristics, units and description of tensile properties of yarn.

Characteristics	Unit	Description
Time to break	s	Time elapsed between the start of the measurement and the breakage of the specimen
Breaking force	gf	Breaking force = maximum tensile force measured
Elongation	%	Breaking elongation = elongation at maximum force

Table 4 Axial tensile properties of single yarn.

Yarn	Time to break	Breaking force	Elongation (%)
Sample-1 mean value	0.233	511.7	3.92
Sample-2 mean value	0.2	412.4	3.15

Table 5 Axial tensile properties of composites.

Composites	V_f	Ultimate stress (MPa) at 0°	Stiffness (GPa) at 0°
Sample-1 mean value	0.305	670.1	31.23
Sample-1 mean value	0.408	744.3	35.01
Sample-2 mean value	0.305	501.2	30.12
Sample-2 mean value	0.408	594.6	33.49

Measured tensile properties of both samples are presented in Table 4. It is clear from the results that mass irregularities cause a decrease in the strength of yarn.

Characterization of tensile properties of composites

Table 5 shows the evolution of average stiffness versus volume fraction of yarn. It can be seen that average stiffness and ultimate stress increases with the increase in volume fraction for both samples of yarn having different amounts of mass irregularities. Furthermore, the mean values of ultimate stress and stiffness obtained for the composite with sample-1 are higher than those obtained for the reinforced composite with sample-2 and the difference increases with volume fraction.

Conclusions

This paper described the influence of volume fraction on the mechanical properties of UPR matrix composites. Experimental values of both stiffness and ultimate strength increase with fiber volume fraction. It was also shown that a great decrease in both mechanical properties occurs with mass irregularities in the yarn structure. Mass irregularities directly influence the degree of microalignment of fibers in the fiber bundles of yarn. Less mass irregularity in yarn offers more strength to yarn and composite. It is therefore instead of raw plant fibers, use of spun yarn is a good option to get better tensile properties of composites. The process of combing of cotton fibers, in spinning system can be used to minimize the mass irregularity in the structure of yarn which has positive impact in micro-alignment of fiber in fiber bundles in yarn.

Conflict of Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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